Unit Two: Waves

A medium is the material that a wave travels through.

A wave can be described as the transfer of energy in the form of a disturbance, often through a medium such as water. It is a travelling oscillator that carries energy from place to place. When a wave travels through a medium, the medium is only temporarily disturbed. When an ocean wave travels from one side of the Mediterranean Sea to the other, no actual water molecules move this distance. Only the disturbance propagates (moves) through the medium.

Types of Waves

Electromagnetic Waves

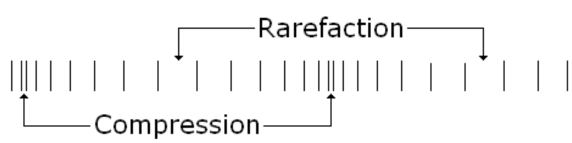
Electromagnetic waves are disturbances that are made up of electrical and magnetic fields. These waves do not require a medium. They travel through space at approximately 3.00×10^8 m/s. Light, x-rays, and radio waves are all examples of electromagnetic waves.

Mechanical Waves

Mechanical waves are disturbances that require a medium to travel through. A slinky, water, and sound are all examples of mechanical waves. There are two main types of mechanical waves – longitudinal and transverse.

Longitudinal Waves

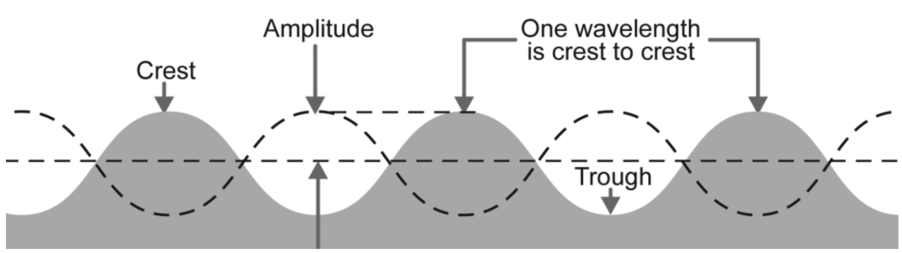
A longitudinal wave causes the particles of a medium to move parallel to the direction of a wave. Sound waves are example of this.



Rarefactions are regions where the particles are farthest apart. Compressions are where the particles are closest together.

Transverse Waves

Transverse waves cause the particles of the medium to vibrate perpendicularly to the direction of motion of the wave.



The uppermost part of the wave is a called a crest. The lowest part is called a trough. The amplitude is the maximum displacement from the rest or equilibrium position. It is a measure of the energy in the wave.

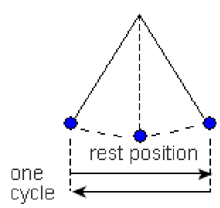
The shortest distance between points where the wave pattern repeats is called the wavelength. The greek letter λ, lambda, represents wavelength. There is one wavelength between crests and one wavelength between troughs.

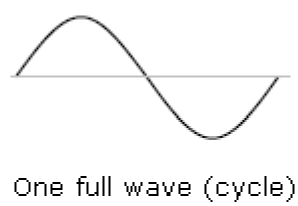
Ex. Sketch a wave with a wavelength 12 m and an amplitude of 2 m.

Periodic Motion

Any motion that repeats itself in regular intervals is called periodic motion. Examples are pendulums on clocks, pistons in a car engine, and your lungs as you breathe. The displacement of a particle during periodic motion is called harmonic motion. The pendulum bob on the clock's pendulum and vibrating guitar strings are good examples of this.

One complete vibrations, or oscillation, is called a cycle. In a pendulum, one cycle is going there and back. In a water wave, it is going up, back down, and returning to the starting level.





A single wave or movement is called a pulse. Regular or repeated waves are called periodic waves.

Period and Frequency

Period (T) = The time required to complete one full cycle

= time / # of cycles

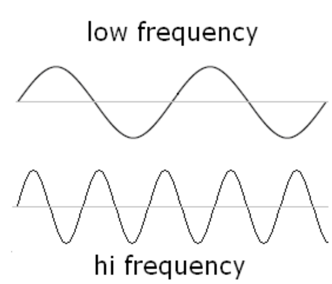
$$T = \frac{t}{cycles}$$

Frequency (f) = The number of cycles or oscillations in 1 second

= # of cycles / time

$$f = \frac{cycles}{t}$$

$$f = \frac{1}{T}$$



From this, we can see that T and f are reciprocal of one another. Therefore:

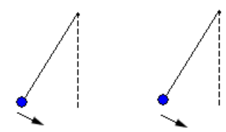
$$T = \frac{1}{f}$$

The unit used to measure frequency is the hertz (Hz), name after Heinrich Hertz. One cycle per second is one hertz.

Phase

In Phase

The diagram below shows pendulums moving in the same direction. They are said to be in phase.



Out of Phase

The diagram below shows one pendulum moving right while the other moves left. They are said to be out of phase.

Ex. How do the windshield wipers on a car move?

Ex. At a Justin Bieber concert, the crowd waves their hands back and forth with a period of 3 seconds. What is the frequency?

Ex. Determine the period of a guitar string that completes 25 cycles in 5 seconds.

Ex. What is the frequency of the guitar string above?

Wave Equation

The speed of a wave is related to its wavelength and frequency. This equation applies to all types of waves:

$$v = f\lambda$$

Where v = speed of wave
f = frequency
λ = wavelength

As period is the inverse of frequency, we could also have:

$$v = \frac{\lambda}{T}$$

Ex. A wave has a wave speed of 243 m/s and a wavelength of 3.27 cm. Calculate:

a. The frequency of the wave

b. The period of the wave

Ex. The wavelength of a water wave in a ripple tank is 0.080 m. If the frequency of the wave is 2.5 Hz, what is its speed?

Ex. The average wavelength of visible light produced by the sun is 500 nm (5.0×10^{-7} m). The frequency of these waves is 6.0×10^{14}Hz.

a. What is the velocity of the sun's light?

b. If the earth is 1.5×10^{11} m from sun, how long does light take to travel from the sun to the earth?

Wave Interference

Principle of Superposition

Two particles cannot be in the same place at the same time. Matter, after all, takes up space. This is not true for waves.

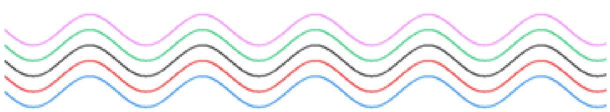
In mechanical waves, when two or more waves cross in a medium, the resultant wave is the sum of the two waves.

Phase difference: A constant phase difference occurs when 2 waves have the same frequency, and different initial phases.

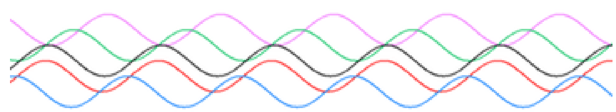
In phase (constructive interference): When two waves have zero phase difference. The resulting disturbance will be larger than the individual disturbances that caused it.

Out of phase (destructive interference): When there is not zero phase difference. The resulting disturbance will be smaller than the individual disturbances that caused it.

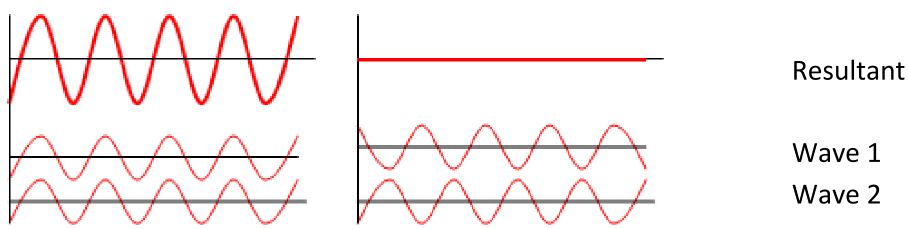
In-Phase Waves:



Out-of-Phase Waves:

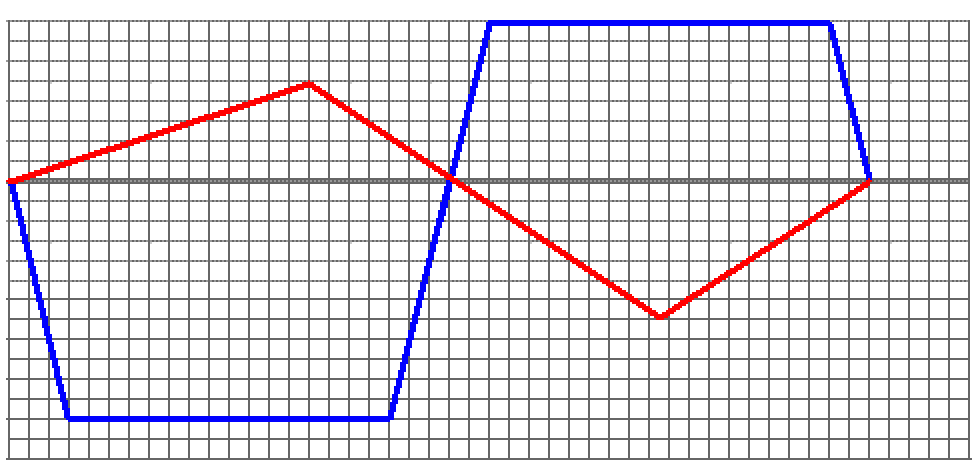


In-Phase Waves: 180° Out of Phase:

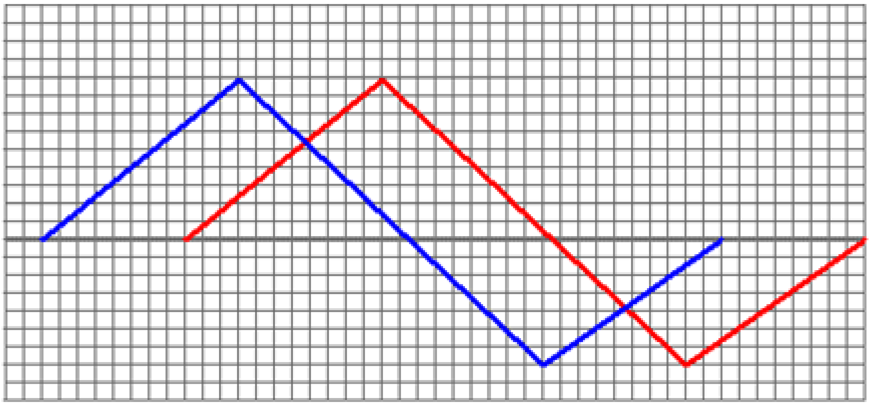


Whenever two or more waves pass through each other, the resulting disturbance at a given point in the medium may usually be found by adding the individual displacements that each wave would have caused.

Ex.



Ex.



Waves at Boundaries Between Media

The speed of a mechanical wave does not depend on the amplitude or the frequency of the wave. It depends only on the properties of the medium. Often, a wave moves from one medium to another.

When a wave travels across a medium it may encounter an obstacle or another medium through which it could travel. The wave can be reflected, such as sound waves reflecting off a canyon to produce an echo, or transmitted, such as sound waves transmitting from water to air to allow you to hear a sound from under water.

When a wave encounters a new medium, part of the energy is transmitted to the new medium, and some of the energy is reflected back. Here is what happens in general:

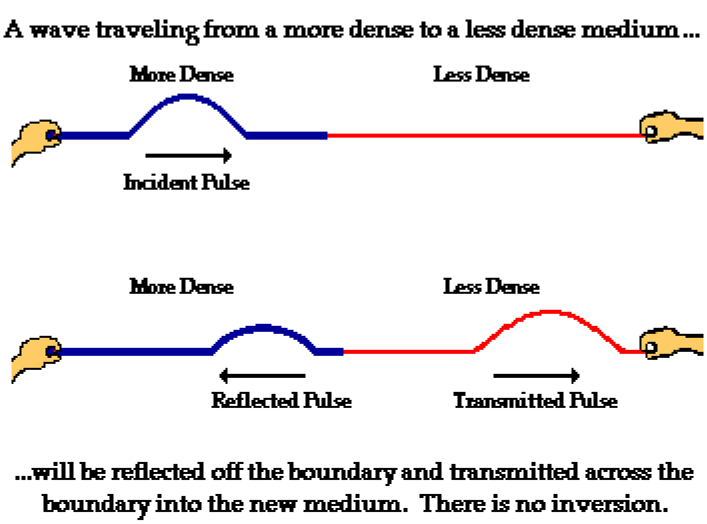
If the new medium is less dense than the first medium:

For the transmitted wave:

- Amplitude increases
- Speed increases
- Wavelength increases
- Frequency remains the same

For the reflected wave:

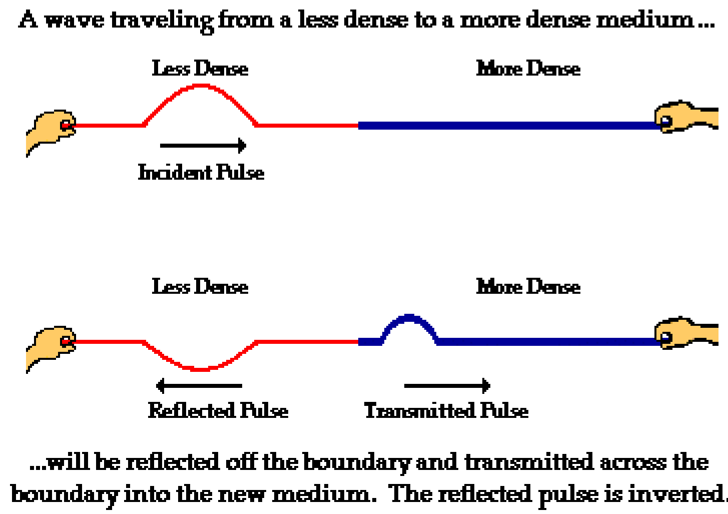
- Amplitude decreases
- Speed remains constant
- Wavelength remains constant
- Frequency remains the same



If the new medium is more dense than the first medium:

For the transmitted wave:

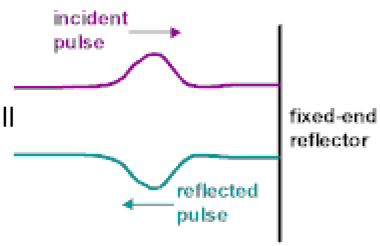
- Speed decreases
- Wavelength decreases
- Frequency remains the same



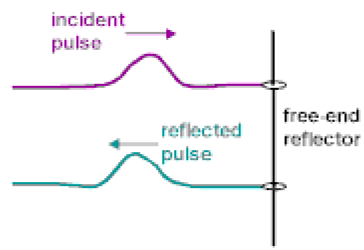
For the reflected wave:

- Amplitude decreases
- Speed remains constant
- Wavelength remains constant
- Frequency remains the same

For a fixed-end, the pulse hits the obstacle that is considered to be infinitely heavy. Therefore, no amplitude is transmitted. The reflected pulse in this case will be inverted.

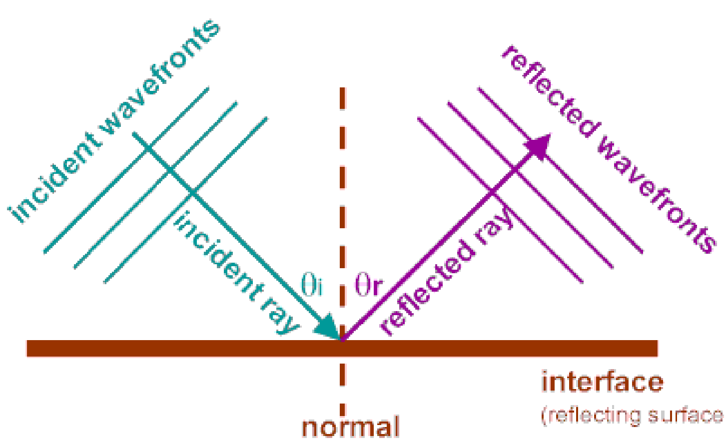


For a free-end, the pulse hits an obstacle that is considered to be infinitely light. When the wave hits this free-end it is reflected upright, as though no obstacle had been encountered.

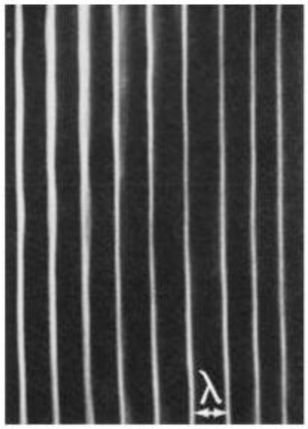


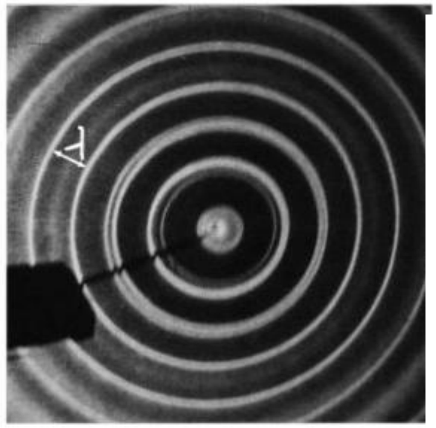
Reflection of Waves

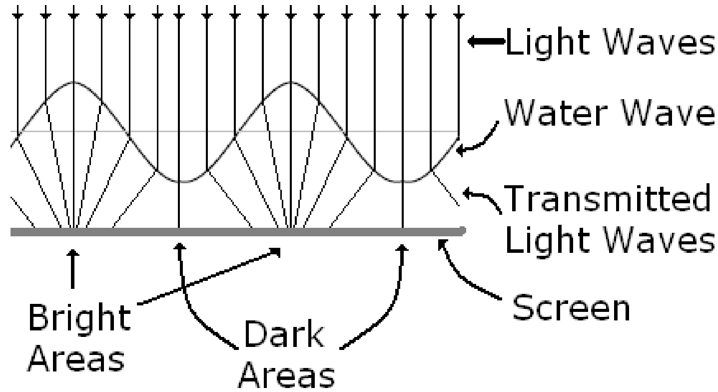
Waves often move in two or more dimensions. Directions of these waves are shown with ray diagrams. A ray is a line drawn at a right angle to the crest of a wave. It shows the direction of the wave and not the actual wave itself. The direction of the barrier is also shown by a line drawn at a right angle to it. This line is called the normal. The angle between the incident ray and the normal is called the angle of incidence. The angle between the normal and the reflected ray is called the angle of reflection. The law of reflection states that the angle of incidence is equal to the angle of reflection.

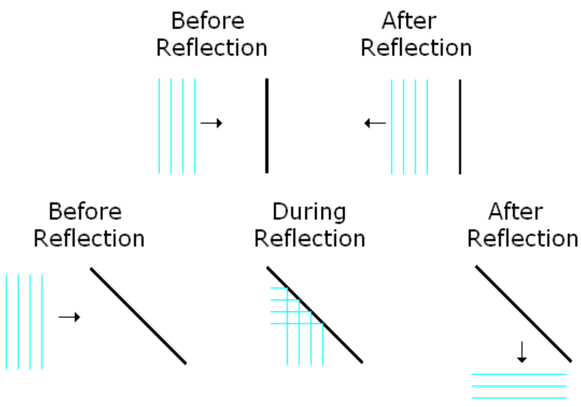


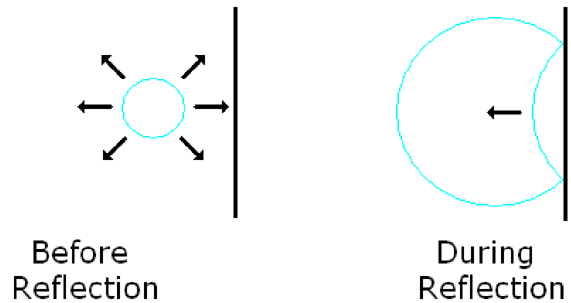
Waves in Two Dimensions



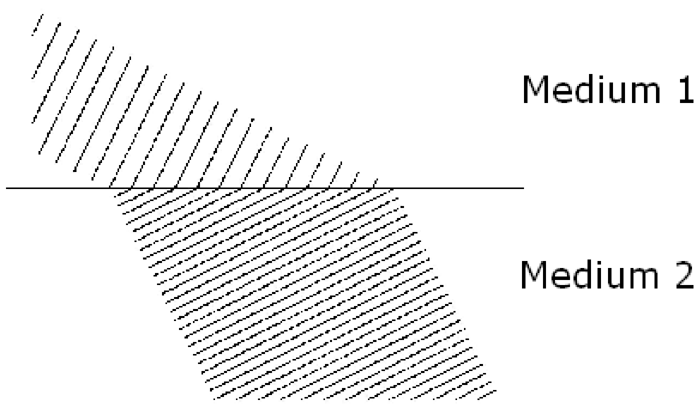








Recall that when a wave enters a new medium, its wavelength changes while its frequency remains the same.



Refraction

In the first media we can say:

$$v_1 = f\lambda_1 \qquad (1)$$

Or rearrange this as:

$$f = \frac{v_1}{\lambda_1} \qquad (2)$$

When the wave enters the second media, the velocities and wavelengths change, so we can alter (2) to say:

$f = \frac{v_2}{\lambda_2}$	(3)

Is there a change in frequency from one media to the next?

Since the frequencies in (2) and (3) are equivalent we can combine equations (2) and (3) to say:

$\frac{v_1}{\lambda_1} = \frac{v_2}{\lambda_2}$	(4)

Or,

$\frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2}$	(5)

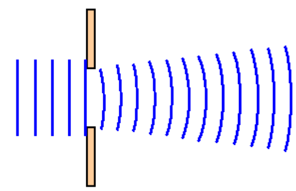
Equation (5) will help us to relate velocities and wavelengths between different media.

Ex. The speed of a sound in air is 344 m/s and has a wavelength of 1.37 m. Determine the speed of sound in water if the wavelength is 5.90 m.

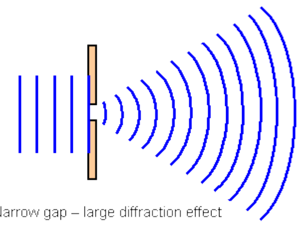
Ex. During your slinky experiment you tied a large coiled slinky to a small coiled slinky. After sending a pulse you notice that the wavelength on the large coil side is 1.5 m and you determine the velocity to be 3.5 m/s. If the velocity on the small coil slinky is 3.0 m/s, what is the wavelength?

Diffraction of Waves

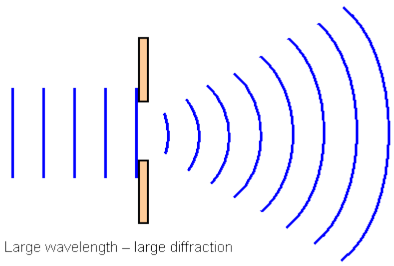
When waves encounter a small hole in a barrier, they do not pass straight through. Instead, they bend around the edges of the barrier, forming circular waves that spread out. This spreading around the edge of a barrier is called diffraction. Waves with long wavelengths are diffracted more than waves with short wavelengths. When a wave passes through a slit, the diffraction is maximized when the wavelength is about the same as the slit width.



Wide gap – small diffraction effect



Narrow gap – large diffraction effect



Large wavelength – large diffraction

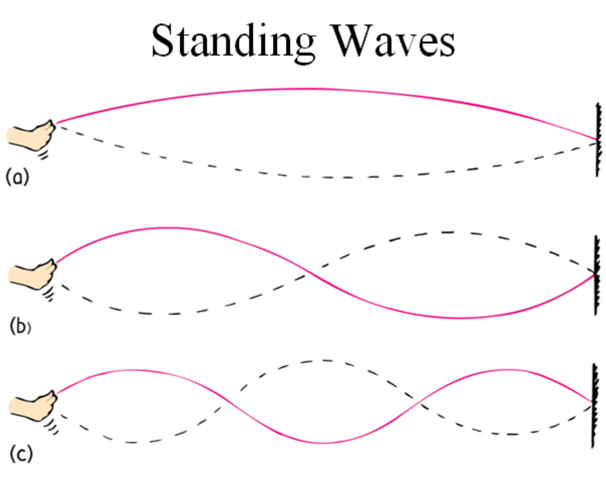
Interference

See Handout.

Standing Waves

Standing waves occur when a string or spring vibrates, like on a guitar, causing a wave travel down one end of the string, reflect off the end of the instrument and travel back down the string in the opposite direction. At certain points along the string the wave traveling in one direction is always out of phase with the wave traveling in the other direction. This leads to destructive interference all the time and the string does not move. These points are called nodes. Nodes are separated by ½ λ. The fixed end in a standing wave pattern in one-dimension is a nodal point

At certain points along the string the wave traveling in one direction is always in phase with the wave traveling in the other direction. This leads to constructive interference and the string has maximum amplitude. These points are called antinodes. Antinodes are separated by ½ λ. Antinodes are separated from nodes by ¼ λ.



For a standing wave to occur:

- the two waves must have a fixed frequency
- there must be a whole number of half wavelengths in the entire pattern

Since the fixed ends are nodal points, only certain frequencies will produce a standing wave pattern. These are the resonant frequencies for that medium.

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